1. Science aim/goal

Probing the Birth of Galaxies through Warm H_2 emission During the Cosmic Dark Ages

2. (i) Scientific Importance:

- A key to understanding the formation of the first galaxies and development of large-scale structure is tracing the cooling of gas into dark matter (DM) halos at early times. During the Universe's first billion years, the initial collapse of gas onto the first galaxy-sized halos is enabled through a mix of quadrupole pure-rotational H_2 and metal fine-structure lines, depending on the degree of enrichment. Collapse is initiated when the gas temperature falls below the virial temperature of the DM halos**.** Observationally, little is known about this period in cosmic history. *Quantifying the collapse of gas into galaxy-sized DM halos in the context of merging sub-halos*, involves an understanding of many complex and poorly understood gas dynamical processes such as supersonic turbulence, shocks, thermal and gravitational instabilities.

- Emission from pure rotational H_2 lines redshifted into the far-IR can provide a direct measurement of the strength of cooling and the dissipation of mechanical energy in the gas as it collapses before the onset of star formation. By analogy with well-studied local shock-dominated, systems, we know that the rest-frame, lowest-lying pure-rotational H_2 transitions can directly trace the energy deposition into cool (typically 120 < T < 1000K) molecular gas from low-velocity shocks and turbulence. The rotational H_2 lines will directly trace energy dissipation in the first collapsing structures. For the redshifted universe, the rotational H_2 lines fall squarely in the far IR, and cannot be observed practically by any known current facility. Gas accumulating in DM halos may also show inhomogeneity in metal enrichment, and measuring the relative strength of H_2 versus the generally brighter metal fine-structure cooling would be an direct observational step towards testing models of early galaxy formation in the dark ages.

- Based on low-*z* analogs (mostly $z < 0.1$), we know that the rotational H_2 lines are key to probing turbulence and shocks, and can often dominate the cooling of gas even in the presence of metals. We know nothing about the importance of the rotational line cooling at $z >$ 2. However, these lines are likely to be powerful and rich in information based on the few observations made at the end of the Spitzer mission for nearby groups, radio galaxies and clusters, including the extremely H_2-bright Spiderweb protocluster at $z = 2$. In more evolved systems, the H_2 lines can even directly trace the total molecular content in galaxies, permitting a direct exploration of the laws governing star formation when other gas tracers like CO and dust fail. Figure (left) shows a mid-IR spectrum of shocked gas in Stephan's Quintet ($z = 0.024$).

- MHD shock-models of molecular gas in low-*z* systems show how H_2 emission can be boosted relative to metal lines, even in strongly metal-polluted gas. Models of shocks in low-metallicity gas will be relevant to gas cooling at high-*z*. Measuring the H_2 and important fine-structure lines ([FeII]25.9μm and [SiII]34.8μm) together in one spectrum will be a powerful test of primordial galaxy-formation models.

2(ii) Measurements Required:

A minimum of two to three of the strongest pure-rotational H_2 lines (e. g. 0-0 S(1), S(3) and S(5)) would be needed to explore the thermodynamic state of the warm (120K < T < 1000K) gas and measure properties such as mass-flow rates and dissipation energy in shocks. To cover $4 < z < 15$ would need bandwidth coverage of 32 - 455μm for the lowest H_2 rotational lines, and obtain PAH features to help distinguish shocks from PDR and other emission processes. ***Spectral and spatial resolution.*** Spectral resolution of at least $R = 500$ (would prefer higher), broad spectral coverage to capture PAH and H_2 lines, several arcsec resolution would be ideal for mapping lensing caustics. **Lensing Survey Strategy—**To amplify the signals to a detectable level (see Fig. (right)) we will need to target lensing caustics in strong lensing clusters to gain amplifications of > 6. Typically lensing surveys at $z = 9$ sample volumes of > 3000 Mpc^3 for tens of cluster targets and larger volumes at lower *z*. At $z = 9$, we expect to find several halos (~1 per 1000 Mpc^3, $M_{halo}=10^{10} M_{\odot}$, $M(H_2) \sim 10^9\ M_{\odot}$) in the sample volume and many more at lower *z*.

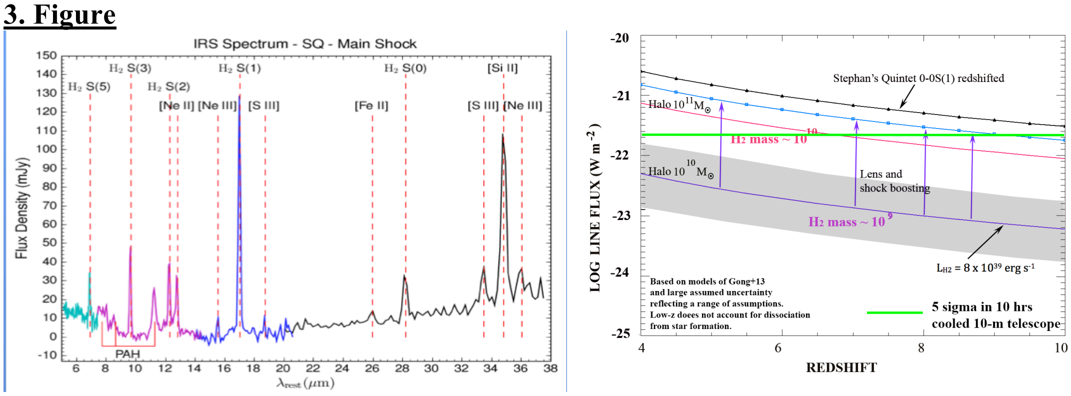
Detection of gas falling into such halos is therefore potentially feasible in very deep surveys at z < 9, especially with additional shock boosting with a cooled 10-m telescope (reaching depths of

few x 10^{-22} W m^{-2} in 5-10 hrs). Note: Stephan's Quintet's local shocked filament (0-0S(1) line luminosity of 4 x 10^{34} W and H_2 mass of 10^9 $M_\odot$) would be directly detectable with a 10-m cooled telescope without lensing at *z* = 9, and we would easily detect similar systems in standard deep sky surveys.

2(iii) Uniqueness to 10µm to few mm wavelength facility: The rotational H_2 lines fall exclusively in the far-IR for gas up to *z* = 11. No other facility is capable of detecting direct H_2 emission from turbulently--heated warm molecular gas in the early Universe. MIRI-JWST will have a limited capability of detecting much warmer H_2 lines to low-z, but will be blind to power in cooler gas where most of kinetic energy resides. The fine-structure lines of [OI]63µm and [CII]158µm can be reached at high-z with ALMA, but there is considerable advantage to detecting redshifted [SiII]34.8µm and [FeII]25.9µm emission in the same spectrometer band as the H_2 lines.

2(iv) Longevity No other facility (including SPICA) can reach the required sensitivity.

3. Figure



Left: Spitzer IRS Spectrum of the Stephan's Quintet shocked filament, showing how shock-excitation can lead to strong rotational lines (Cluver+10). Note also the bright [SiII]34.8µm line, a line expected to be much brighter than the H_2 lines in the diffuse early collapse of a galaxy-sized halo. Right: Estimated line fluxes for 0-0S(1) or S(3) H_2 lines derived from models of Gong+13 for two large DM halo masses (purple and red lines) as a function of z. We also show the amplification of a factor of 6 or more from lensing and 5 (total 30) from possible shock boosting in the $10^{10}M_\odot$ halo. At z = 9, we expect several such halos in the lensing caustics of a sample of lensing clusters and many more at lower z. Stephan's Quintet's 17λµm H_2 emission luminosity (black line) would be detectable to large z without lensing. Observations to this depth will test models by determining how strong H_2 lines are relative to fine-structure lines.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	µm	32-275*	32-455**	*0-0S(1),S(3),S(5) or **S(0)-S(5) H_2 line coverage for 4 < *z* <15
Number of targets	N_{cl}	18	18	18 Strong lensing clusters
Survey area	beams	30	30	Beams per cluster
Angular resolution	arcsec	2-5 arcsec	2-5 arcsec	Beam to cover range of lensing caustics scales
Spectral resolution	$\Delta\lambda/\lambda$	> 500	1000 or more	600 km/s resolution adequate, higher is desirable for kinematics
Bandwidth	µm	240	420	
Continuum Sensitivity (1 σ)	µJy	NA	NA	

Spectral line sensitivity (5 σ)	W m^{-2}	4-8 x 10^{-22}	2 x 10^{-22}	Required to reach $z < 7$ Desired to reach $z \sim 9$